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SHORT COMMUNICATION

Outlook on ecologically improved composites for aviation interior and secondary structures

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Abstract
Today, mainly man-made materials such as carbon and glass fibres are used to produce composite parts in aviation. Renewable materials such as natural fibres or bio-sourced resin systems have not found their way into aviation, yet. The project ECO-COMPASS aims to evaluate the potential applications of ecologically improved composite materials in the aviation sector in an international collaboration of Chinese and European partners. Natural fibres such as flax and ramie will be used for different types of reinforcements and sandwich cores. Furthermore, the bio-based epoxy resins to substitute bisphenol-A based epoxy resins in secondary structures are under investigation. Adapted material protection technologies to reduce environmental influence and to improve fire resistance are needed to fulfil the demanding safety requirements in aviation. Modelling and simulation of chosen eco-composites aims for an optimized use of materials while a life cycle assessment aims to prove the ecological advantages compared to synthetic state-of-the-art materials. In this paper, the status of selected ecologically improved materials will be presented with an outlook for potential application in interior and secondary structures.

Keywords Aviation · Eco-composite · Bio-fibre · Bio-resin · Interior · Secondary structure · Sandwich · Hybrid · Recycling

1 Background

Lightweight structures made from composite materials have gained in importance due to their excellent mechanical properties combined with relatively low weight. Fibre reinforced polymers (FRP) enable the construction of lighter and more efficient aircrafts resulting in the reduction of fuel consumption and increased payloads. High performance composites such as carbon-fibre reinforced plastics (CFRP) are used in primary structures of modern aircrafts such as Airbus A350 (Fig. 1) and Boeing 787 Dreamliner. They have been used more and more to replace the classic materials such as aluminium or titanium. Furthermore, glass fibre reinforced plastics (GFRP) sandwich with phenolic resins as matrix system find their application in the interior due to their low weight to stiffness ratio.

But all these composite materials currently used in aviation have one thing in common: they are man-made and especially the carbon fibres are very energy intensive in the production. Renewable materials such as bio-fibres and bio-resins have been under investigation for a long time for their use in composites but they have not been introduced into a modern aircraft in noticeable amounts yet.

From ecological perspective, composites such as GFRP and CFRP typically consume a higher amount of energy during the production phase compared to classic metals. Furthermore, their intrinsic heterogenic structure impedes a similar efficiency when it comes to recycling at the end of

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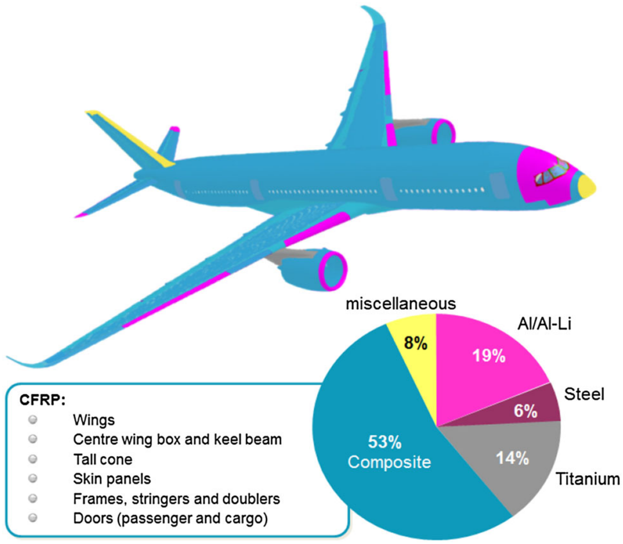

Fig. 1 Materials used in a modern aircraft, the Airbus A350 [1]

life. A close-loop recycling as with metal is not possible and leads mainly to downgraded recyclates. On the other hand, the lightweight potential of GFRP and especially CFRP is very valuable to reduce fuel consumption in transportation applications depending on travel distance and life-time. Here, the relation of ecological impact between production phase and use-phase is shifted towards the latter. Nevertheless, it is of high interest to reduce the consumption of energy intensive carbon and glass fibres in favour of bio-based fibres in certain applications.

As safety is of primary importance in aviation, the lack of experience and confidence in the long-term performance and mechanical properties of composites made of renewable materials is still an obstacle for their usage. It is, therefore, at the moment out of scope to substitute high performance and safety-relevant composites such as CFRP or GLARE in primary structural parts of the aircraft, for example, the fuselage frame and the outer wing box, with bio-based materials. On the other hand, secondary structures and interior composites which are not stressed on such high levels offer possible areas of application. Examples for secondary structural parts are fairings and the landing gear doors. In the interior, cabin ceiling panels, sidewalls and floor panels are aims for the substitution of glass fibres and phenolic resins with ecologically improved developments.

2 The eco-compass project

The European Union has a long history of enabling research for aeronautical materials to increase the environmental performance of aircraft with projects such as Clean Sky in Horizon 2020 and precursor framework programs. In the GRAIN project (GReener Aeronautics International Networking), Chinese and European partners identified possible research areas of mutual interest, such as composites made from renewable materials and function-integrated carbon fibre structural composites. The time is now right for promoting the introduction of ecologically favourable materials into the aviation sector with the help of the ECO-COMPASS EU-China project.

ECO-COMPASS stands for “Ecological and Multifunctional Composites for Application in Aircraft Interior and Secondary Structures”. It is a Horizon 2020 research and innovation action (RIA) project with overall 19 partners from Europe (8) and China (11). The Chinese partners receive funding from the Chinese Ministry of Industry and Information Technology (MIIT). The main objective of the project ECO-COMPASS is to develop and assess ecologically improved and multifunctional composites for application in the aviation sector. Therefore, it will bundle the knowledge of research from participants in China and Europe to develop ecologically improved materials for their application in aviation structures with a better ecological balance than materials currently used.

The application of renewable materials especially in both aircraft secondary structures and interiors is a very ambitious objective due to the stringent requirements. However, the impact of the results could reach much further than aerospace industry with its challenging requirements to ensure the safety of the passengers. Ecological composites that are improved regarding their mechanical, multifunctional and ageing properties are also very interesting for other transportation industries such as automotive, train and marine. Furthermore, other sectors such as wind energy and recreational equipment could profit from the results.

Ecologically improved does not necessary mean that only bio-based materials will be evaluated. Recycled materials and technologies to enhance the multifunctional aspects of composites have to be investigated, too (Fig. 2). For example a material protection technology that is needed in case of using bio-based fibres such as flax or ramie for interior applications is an adapted fire protection. These and other technologies could be combined and will be evaluated for their use in the aerospace industry not only on technical readiness level (TRL) but also on environmental impacts compared to selected state of the art parts with an accompanying life cycle assessment (LCA).

3 Application scenarios for eco-composites in aviation

It must be distinguished between the identified applications: secondary structures and interior. The requirements of those applications differ considerably and, therefore, different ways

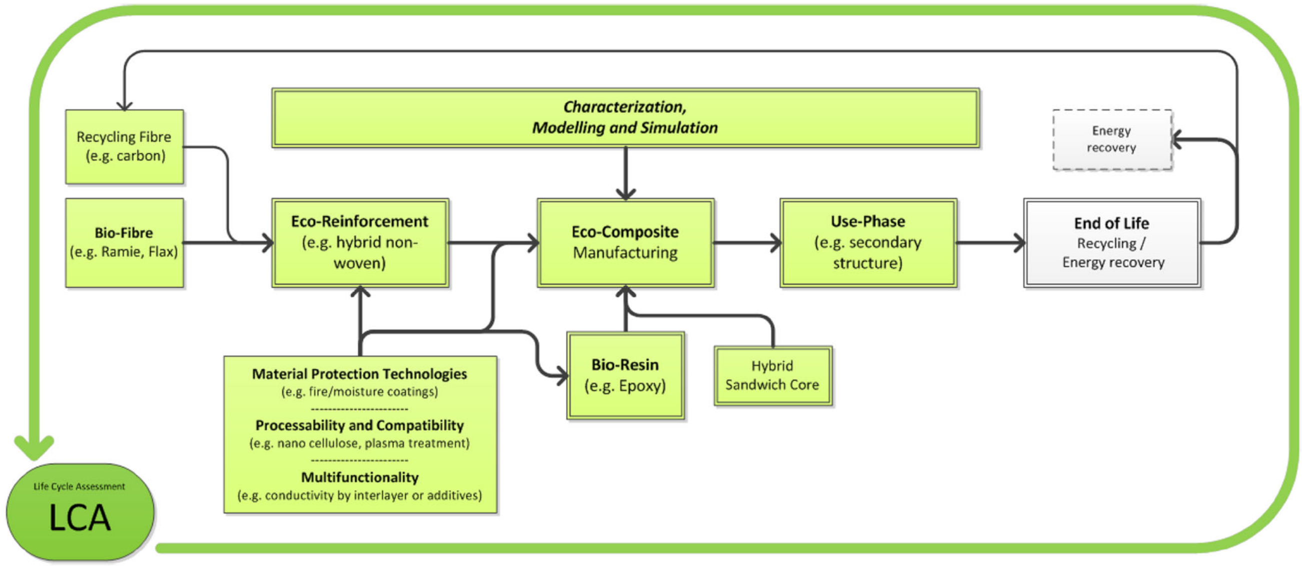

Fig. 2 Simplified circular flow diagram for ECO-COMPASS tasks

to meet these requirements are planned in ECO-COMPASS. The focus for interior materials (Fig. 3) will be on the fire properties (flammability, heat release, smoke and toxicity) and multifunctional benefits that can be achieved by the use of natural fibres, e.g. acoustic damping. On the other side, the secondary structures have higher requirements regarding the mechanical properties of the composite. The influence of environmental impacts such as moisture, ultraviolet radiation and lightning strike will be taken into account in ECO-COMPASS. Apart from secondary structures the Chinese partners will evaluate an approach to enhance the conductivity of composites by interlayers. This will also be applicable for high performance CFRP used in primary structures.

Pure bio-composites made of bio-fibres (e.g. flax, ramie) and bio-resin (e.g. epoxy) will be evaluated in parallel with

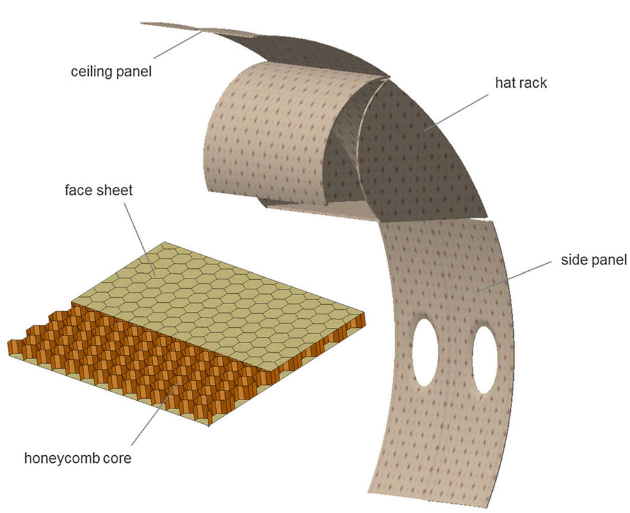

Fig. 3 Examples for interior sandwich parts

a new approach that aims to combine valuable recycled carbon fibres and bio-fibres in a hybrid non-woven. Together with natural fibre semi-finished products developed in China (woven, unidirectional reinforcements), this will enable the aircraft engineer to select the right material for the desired application. Fibre treatments to enhance the mechanical properties and processability of natural fibres will be proposed from partners in Europe (e.g. plasma treatment) and China (e.g. nano-cellulose) with the aim to improve the fibre-matrix adhesion which is crucial for best properties of FRP. Furthermore, novel hybrid material solutions for sandwich cores will be evaluated.

In parallel to the work on ecological reinforcement fibres the development of bio-sourced resins as substitutions for the currently used bisphenol-A based epoxies and phenolic resins will be carried out. On the Chinese side, three different and promising bio-epoxy variants will be optimized and evaluated for this task. As epoxy resin will be mainly interesting for load-carrying applications the European partners will in parallel evaluate the market situation on bio-based resins to replace the phenolic resin that is used in the cabin environment today.

As the use of biological materials brings new challenges such as moisture sensitivity and fungal attack, special attention will be paid to adapted protection technologies. Solutions to mitigate these environmental influences will be identified and tested, e.g. special coatings that do not influence the mechanical behaviour of the composites. Furthermore, fibre treatments (sizing) and resin additives such as effective nanoparticles to enhance these crucial properties will be assessed. It will be of high importance in the project that these protection technologies should only be applied if they are necessary to fulfil their desired function as every further material and treatment potentially increases the ecological footprint, cost and weight. Therefore, an evaluation of the environmental impact will be carried out not only by technical means but also regarding their ecological impact with the help of a life cycle assessment.

Life cycle assessment (LCA) is used as analysis tool to evaluate how a product or material potentially affects ecosystems. This should possibly include all life stages from the start of production to the end-of life. The ISO framework of LCA is standardized in the ISO 14040-14044 and defined as "the collection and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle". LCA allows the systematic quantitative assessment in terms of environmental impact, human health and resource consumption. Examples for environmental impact categories are acidification potential, global warming potential and human toxicity potential. Also factors such as land-use, noise generation and loss of biodiversity should be included in a LCA.

To reduce the effort of certification tests, a numerical simulation of the developed composites will be of high value to assess the improvements and challenges of the proposed materials. It is well known that the use of the finite element method (FEM) allows for a significant reduction of the required certification tests of structural elements, components or full scale structures. Even though this project is not accounting for high responsibility load bearing components but mainly for secondary structures and interior parts, the use of numerical tools will assist the mechanical characterization of new materials stage and consequently the associated cost. Structural, thermal as well as electromagnetic numerical analysis will be performed and validated by the Chinese and European partners. Finally, when all numerical analyses are validated and offer good agreement with experimental results they will be used for the design optimization of new eco-composites.

A compromise between the required materials properties, cost and ecological impact has to be found for every application in a specific way. This means any eco-material may be used on its own and does not necessarily need to be combined with the other eco-materials but with state of the art materials already used to achieve a positive effect. A possible scenario is the use of bio-resins with standard man-made reinforcement fibres in applications where higher mechanical properties are of importance or the environmental influence impedes the use of bio-sourced fibres.

4 Outlook for eco-materials

Current state-of-the-art materials in aircraft cabins are very stiff and lightweight sandwich panels used for instance in the ceilings, linings and hat racks. These sandwich panels contain a core made of aramid fibres and phenolic resin. Glass fibres are used in combination with the phenolic resin as prepreg-reinforcement for the top-layers of the sandwich (Fig. 3). These very light and stiff panels are manufactured in a heated press. No ecologically satisfactory end of life treatment is available for such sandwich panels because of the usage of phenolics and glass/aramid fibres. The separation of such heterogenous material combinations embedded in a crosslinked thermoset resin is very complex [2, 3].

The secondary structural parts require materials with higher mechanical properties. Because of weight and mechanical requirements, continuous carbon fibres are mainly used for such parts. To protect the electromagnetic interference and particularly the lightning strike, electrical conductive structural composites are desired to use in the critical zones of aircraft. The state-of-the-art carbon composites cannot satisfy the requirements. This is a big technological challenge for the polymer matrix composites [4–10].

4.1 Reinforcement fibres

A multitude of bio-fibres is available on the world market. In Europe, flax and hemp fibres are the most common bast-fibres used to reinforce composites. Ramie fibres that are grown in China are another suitable candidate. A drawback of natural fibre reinforced plastics (NFRP) is their lack of strength compared to glass and carbon fibre reinforced plastics (GFRP, CFRP). In theory, natural fibres can reach very high values for tensile strength of up to 1000 MPa but due to imperfections (kink bands) and incompatibilities to certain resin systems their potential cannot be fully used [2, 10]. The poor interfacial bonding properties between hydrophilic natural fibres and hydrophobic polymers lead to low mechanical properties of NFRP. Therefore, improving the interfacial strength and toughness is necessary in order to improve facilitate their full potential. On the other side, the low density of bio-fibres leads to good specific stiffness values comparable to GFRP with further advantages on acoustic and thermal damping due to their hollow structure, the lumen (Fig. 4) [11].

Based on previous successful research experiences on using chemicals and CNTs to improve the interfacial properties of NFRP, the application of nano-natural cellulose to modify the interfacial and interlaminar properties of the composites will be investigated [12]. In a Chinese study, zirconia nanoparticles (ZrO_2) were designed and grafted onto flax fibres by hydrogen bonds as seen in Fig. 5 [13]. The results are an increased tensile strength of the grafted flax fibres while the tensile modulus is not affected. Another positive effect of ZrO_2 grafted fibres is the

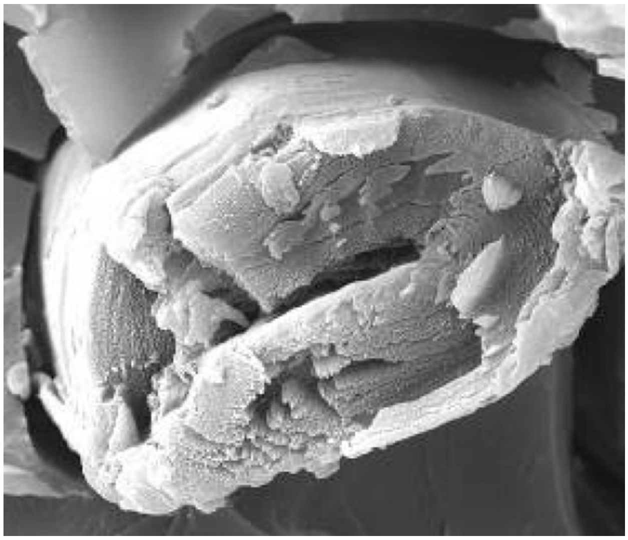

Fig. 4 Cross section of a ramie fibre [11]

reduced grow of fungal colonies on flax fibre reinforced epoxy composites.

Another topic of ECO-COMPASS is the evaluation of recycled carbon fibres (rCF). New carbon fibres are very expensive due to their energy intensive production process. It is, therefore, of high importance to reuse these valuable fibres in order to save energy, raw materials and cost. Pyrolysis of CFRP is a process that has made it into industrial use recently to regain carbon fibres from composite waste. These recycled carbon fibres (rCF) are available in milled and chopped form. The restricted length and the removal of the fibre sizing are their main drawbacks compared to virgin carbon fibres (vCF) [14, 15]. It is, therefore, at the moment not possible to give these "downcycled" fibres the same function as virgin carbon fibres.

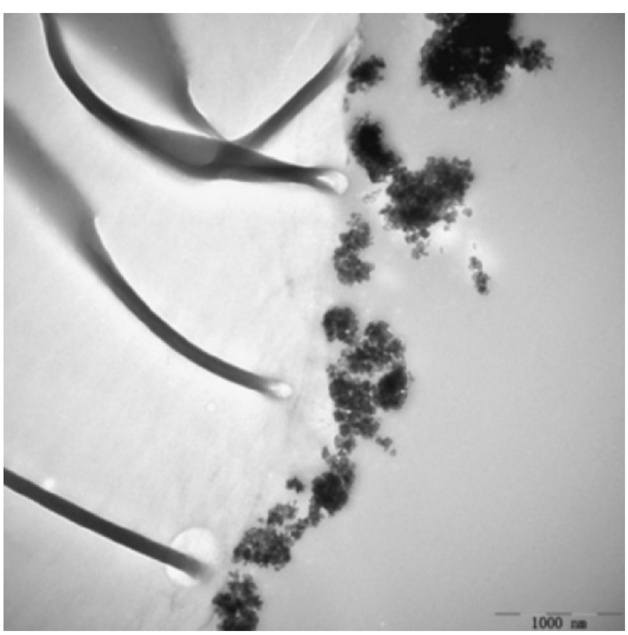

Fig. 5 Nano particle aggregation on a flax fibre [13]

In parallel to classic reinforcement types used in aviation, the combination of renewable bio-fibres and recycled carbon fibres in a hybrid non-woven will be evaluated as an alternative way to find applications for a rising amount of recycled carbon fibres (Fig. 6). Recycled carbon fibres have short and variable length which makes it very difficult to convert them into continuous yarns for traditional woven reinforcements. Non-woven processes are capable of combining different types of fibres of variable length in a single web structure for composite production. Nonwoven processes are also less expensive and more eco efficient compared to classic woven fabrics from bio-fibres due to their simpler production process [3]. Renewable bio-fibres such as flax and PLA have been successfully combined to produce bio-degradable nonwoven composites [16–18]. The combination of recycled carbon fibres with bio-fibres could enable the designer to optimize multifunctional eco-efficient composites using their inherent advantages.

4.2 Bio-based polymeric resins

Today, thermosets are the most important polymer family used in the aviation industry [19], due to their versatility, high performance and the wide span of applications they comprise. Mainly phenolic and epoxy resins are used for the interior panels and secondary structures of aircraft [20, 21]. However, their petrochemical base and the difficulty of thermosets to be recycled, forces the industry to seek for feasible alternatives that can reduce the ecological footprint associated to their production [21].

In ECO-COMPASS, promising bio-based resins will be assessed for their use in aerospace applications. Thermosetting epoxies from rosin, itaconic and gallic acid (Fig. 7) have been identified as candidates from China, due to their aliphatic-cyclic structure which can outperform existing solutions in terms of mechanical properties and chemical resistance [22–24]. Other bio-based resins show very promising fire properties comparable to phenolic resins. As an example, Fig. 8 shows the results of flammability tests with glass and bio-fibre reinforced

Fig. 6 Combination of flax fibres and recycled carbon fibres in a hybrid non-woven

composites. The burn length is the distance of damaged area to specimen edge due to the combustion during the flammability test. Selected (at least partly) bio-based resins [epoxy (EP), furfuryl alcohol based resin (FUR) and linseed acrylate resin (ACR)] have been compared to phenolic resin (PF) as reference. The furfuryl alcohol based resin shows results in the range of the phenolic reference when it is reinforced with glass fibres. Furthermore, the need for flame retardants in case of using bio-sourced fibres is clearly visible as none of the specimens reinforced with flax fibres passed the test with the threshold of a maximal burn length of 152 mm [2].

The incorporation of additives within the resins will be analysed to enhance the performance of neat resins and subsequent composite manufacturing. With this purpose, application of carbon based additives such as graphene, graphene oxide [25] or CNT [26], as well as silicon carbide nanoparticles (nanotubes or nanowhiskers) could be highly efficient in terms of thermal conductivity enhancement [27–29], along with electric conductivity [30] and enhancement of mechanical properties [31, 32]. Furthermore, specific coupling agents will be employed to enhance the compatibility with additives and fibres. On the other hand, fire resistance properties will be enhanced by means of nanotechnology and innovative halogen-free phosphorous based reactive fire retardant additives, covalently linked to the neat resin [33].

4.3 Composite manufacturing

The final composite material properties are related to the control of the processing parameters during the manufacturing. The choices of the appropriate pressure, temperature and curing time are matter of importance to obtain low porosity contents and an important extend of cure.

As different bio based materials will be considered in the ECO-COMPASS project, a physico chemical characterization campaign will be done to identify the polymerization kinetics and the rheological behaviour of the materials to be transformed. These tests, which will also be carried out on formulations with fillers for multifunctional properties enhancement, will allow the identification of the most suitable process windows to guarantee the best compromise between high material properties, and limited curing cycle

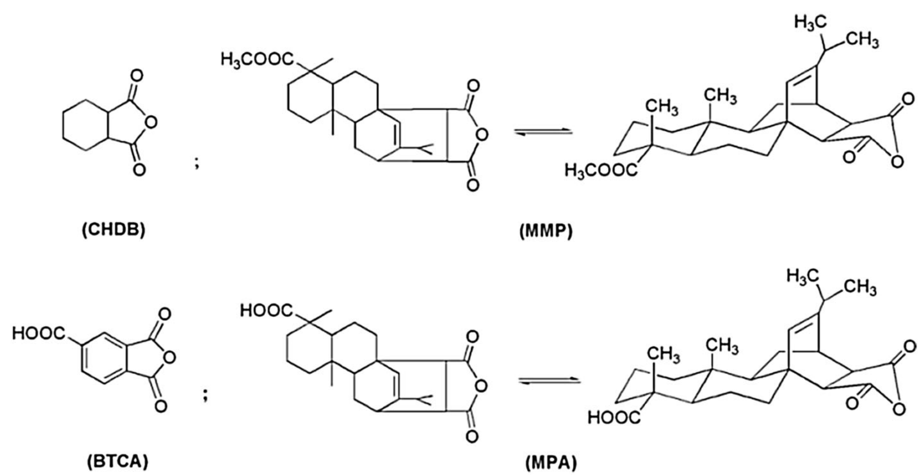

Fig. 7 Chemical structures of rosin-based curing agents MMP and MPA and petroleum-based curing agents CHDB and BTCA [24]

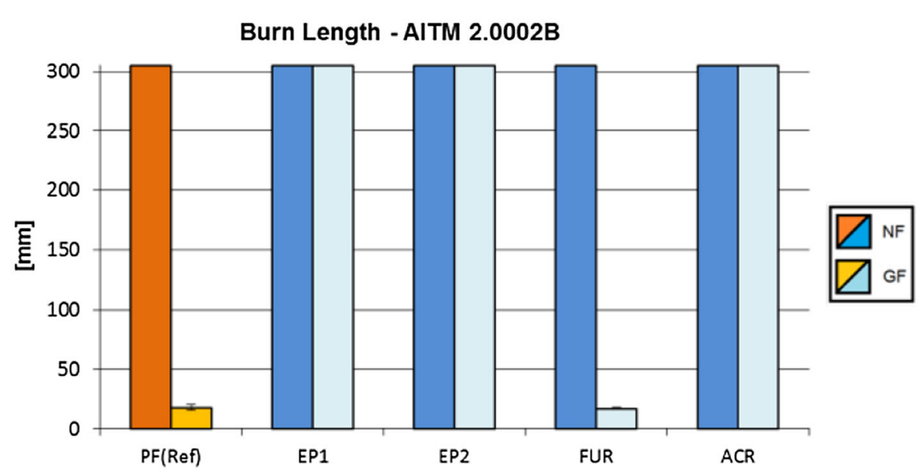

Fig. 8 Burn length of glass and bio-fibre reinforced composites [2]

time. As bio based materials are usually very sensitive to the environment and show bigger deviation standards on properties than "non bio-based" materials, such definition of the curing cycles parameters are critically important to maximize the process reliability and to increase the repeatability of the final properties of the materials manufactured.

Then, composite laminates and sandwich composites will be manufactured by autoclave and hot press. Thanks to resin and fiber formulations with fillers, an enhancement of the material performances is targeted, such as structural and mechanical properties, structural damping, fire/smoke/toxicity and hygrothermal ageing properties. Samples lay ups and dimensions will be chosen according to aeronautical specifications and standards, and material health will be preliminary controlled by ultrasonic testing before characterization.

Material protection will also be evaluated to improve the durability of the material manufactured regarding environmental attacks and fire smoke and toxicity properties, but will require a study of the compatibility of the material with these solutions. For the different applications (secondary structures and interior parts), a special attention will be paid to the total weight increase induced by the material protections, which will be parameter for the choice of the coating. Of course, synergies between the different requirements will be looked for between the different solutions evaluated.

4.4 Modelling and simulation

The objective of ECO-COMPASS research is to design, improve and optimize the eco-composites to be used in an efficient way in (semi-)structural parts. The mechanical–numerical proposal for such purpose consists of an investigation addressed to obtain good mechanical properties, durable, and resistant eco-composites based on rational analysis that provides by the adaptation of generalized mixing theory and/or multiple scale homogenization theory [34–36], derived from the formulations for the classical composite material, and all these mechanical formulations within a framework provided by the genetic algorithms optimization [37, 38]. So, the proposed procedure promises a detailed behaviour study of the whole composite, starting from each one's simple component behaviour. It seeks to obtain sustainable materials which are also mechanically and thermally efficient.

Multiscale procedures are based in analysing a material model (micro-model), assuming a periodic distribution of the material within the structure. This analysis provides the material response, which can be used in a structural model (macro-model) to obtain the global performance of the structure. There are several approaches in which a multiscale procedure can be defined. The generalized theory of mixtures or serial/parallel mixing theory [34, 39] proposes a phenomenological homogenization in which the composite performance is obtained from the constitutive models of its components and some closing equations that define how these components interact among them. This formulation is capable of accounting for complex failure procedures such as delaminations, with an affordable computational cost [40, 41].

The other multiscale approach that will be used consists in obtaining the composite performance from the analysis of a numerical model of a representative volume element (RVE). The boundary conditions to be applied at the RVE come from the macro-model and the response obtained

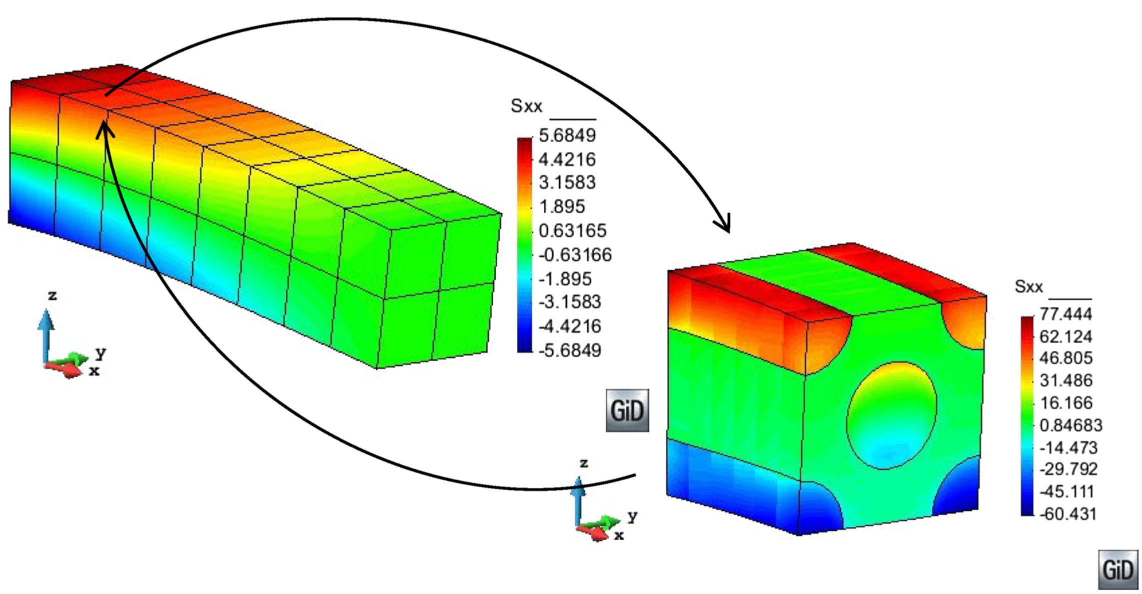

Fig. 9 Stresses in the macro and micro models of a clamped pultruded composite beam [40]

from the RVE is transferred to the structural model. An example on how a multiscale analysis works is shown in Fig. 9, in which are plotted the stresses obtained in the macro and micro scales for a clamped beam made with a pultrusion composite. As it is shown by Otero et al. in [42] the main drawback of this approach is its computational cost. For this reason, ECO-COMPASS project will look into two different strategies to reduce it. One consists of defining a comparison parameter capable of predicting if a given material point might have reached its threshold stress–strain state. His approach has been formulated in [43] and has shown an excellent performance. The second approach consists of analysing the failure of RVE under different stress–strain states to create a material database defining the failure threshold and its evolution. This approach requires an initial computational effort to define the database but, afterwards, the structural simulation can be conducted quite easily.

All formulations developed to analyse composite structures require, also of accurate material models to characterize the constituent materials. The working group involved in ECO-COMPASS will use advanced constitutive models for the materials [44, 45], together with specific formulations to account for large anisotropy behaviour [46], or plastic mechanical damage and moisture content [47]. The optimal material design [37, 38] in terms of the structure and its uses depending on the climatic conditions of the place also will be considered through thermal treatment of conduction and diffusion.

The use of virtual design and optimization models that will be developed in ECO-COMPASS will reduce the development time and cost of multifunctional eco-composites by reducing the number of manufacturing trials and experiments. Investigation is carried out on the understanding of material parameters and processing factors affecting the mechanical, thermal and electrical properties of bio-polymer nanocomposites as well as the electromagnetic shielding properties and lightning strike behaviour of eco-composites using numerical [48–51] and/or analytical models. The material parameters considered are the nanofiller dimensions, the nanofiller configuration, the properties of the nanofiller/matrix interphase and the properties of the bio-polymer and fibres. The processing factors considered are the nanofiller volume fraction and the formation of agglomerates of nanofillers. The investigation is conducted by means of representative unit cells (RUCs) of nanofiller agglomerates developed using the DIGIMAT software. The RUCs are solved numerically using the finite element method and analytically using the Mori–Tanaka method. At the same time, homogenization of the RUCs is applied through the use of periodic boundary conditions. The models will receive input from microscopy images (SEM, AFM, etc.) and will be validated against mechanical, thermal, electrical, EMI and lightning strike tests.

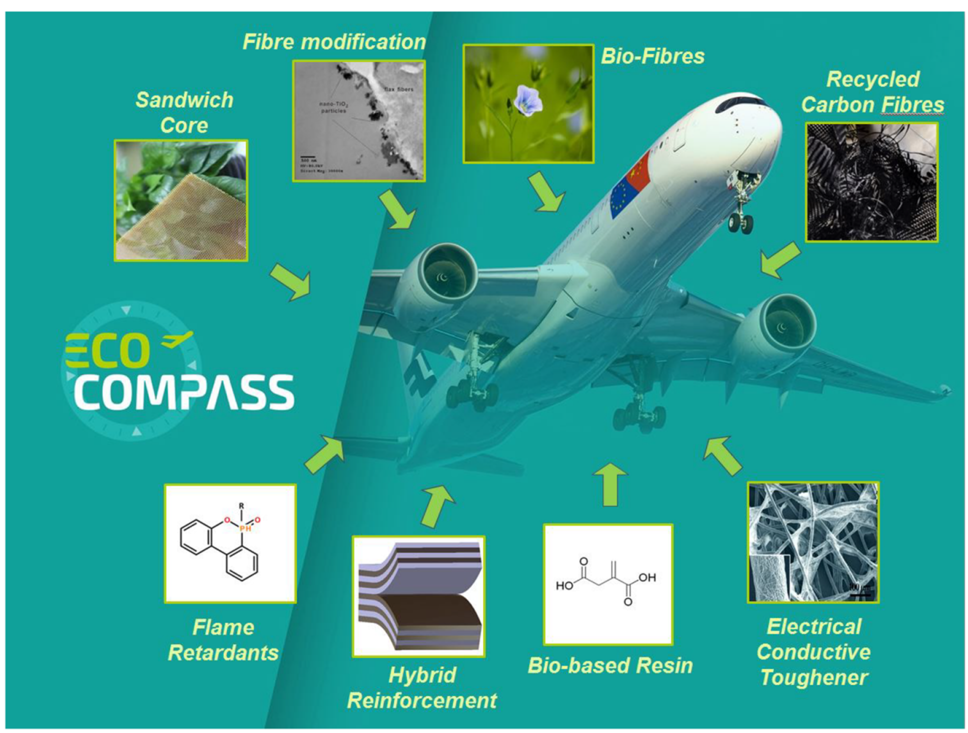

Fig. 10 Examples of materials and technologies under investigation in ECO-COMPASS

5 Conclusions

Lightweight structures made from composite materials have excellent mechanical properties combined with relatively low weight. These high-performance composites used today in aviation are mainly based on man-made components such as carbon fibres. Bio-sourced materials such as flax fibres offer very promising characteristics but have not found their way into aviation, yet. The project ECO-COMPASS aims to bundle the knowledge of research in China and Europe to develop ecologically improved composites for the use in aircraft secondary structures and interior. Therefore, bio-based/recycled reinforcements, resins and sandwich cores will be assessed and optimized for their application in aviation (Fig. 10). To withstand the special stresses in aviation environment, protection technologies to mitigate the risks of fire, lightning and moisture uptake will be investigated while an adapted modelling and simulation will enable the optimization of the composite design. Electrical conductive composites for electromagnetic interference shielding and lightning strike protection will be investigated as well to improve the overall properties of high-performance composites. A cradle to grave life cycle assessment (LCA) will be carried in parallel to compare the eco-composites with state-of-the-art materials.

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